MINI REVIEW

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Photo by John Flower

Vern Sandberg of P-25 checks instrumentation in the interior of the electronics hut before an LSND experimental run. The purple modules in the background measure the time and charge of each phototube signal, and the colored lights on the front panels indicate the rate of phototube hits. The gray power supplies on the right provide high voltage for all of the phototubes in the detector.

Neutrinos: An Elusive Reality

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We are immersed in a sea of particles that had their beginnings in a "big bang." In the earliest moments of the big bang when the temperature was exceedingly high, the universe expanded rapidly and space was filled with many elementary particles and their antiparticles. Among the cosmic debris, neutrinos and photons of light condensed out and escaped the annihilation that occurred as the early particles collided during the rapid expansion. As the temperature began to fall, neutrons and protons came together to form light nuclei, which attracted negatively charged electrons to form neutral atoms. Thus began the formation of the substructure of everything around us. Among the surviving elementary particles from the big bang, neutrinos and photons still traverse the universe in vast numbers.

Once thought of as figments of the scientific imagination, neutrinos are included in a class of particles that provide structure to our universe. Another class of particles gives rise to the four fundamental forces that hold the universe together. The interactions between these particles are described by the Standard Model, which has been the theoretical basis behind the substructure of the universe. However, an experiment contrived by members of the Subatomic Physics Group (P-25) of the Physics Division at Los Alamos is probing the fundamental properties of the neutrino. If successful, this unique experiment may cast light on broader questions concerning the origin, and perhaps end, of the universe.

The existence of the neutrino was first postulated in 1930 by Wolfgang Pauli to reconcile the observation of energy production in radioactive decay with the principle of conservation of energy. Energy can supposedly be transformed from one form to another but not created or destroyed. Pauli speculated that when electrons were emitted in the decay of radioactive nuclei, some of the energy that seemed to be missing was carried away by an unobserved and elusive particle. This second particle was dubbed the neutrino, or "little neutral one." We now believe that Pauli's neutrino, the electron neutrino, is one of three flavors of neutrinos. Like the electron neutrino, the other two—the muon and tau neutrinos—are named after their associated charged particles, the mu meson (muon) and the tau meson (tauon). Moreover, each neutrino flavor has its associated antiparticle.

At Los Alamos, we designed and built a unique liquid scintillator neutrino detector (LSND) to look for the emergence of the antielectron neutrino. If seen, we can conclude that neutrinos can transform from one flavor of neutrino to another in the course of passing from the point where they are produced to the detector site. For this to happen, neutrino flavors have to "mix," and the masses must be different from zero. However, the Standard Model assumes that the neutrino mass is zero, although recently this assumption has been questioned. From a nuclear and particle physics standpoint, the neutrino is one of the few remaining elementary particles whose mass still remains an open question—and a very important one at that. This question of neutrino mass has substantial implications for particle-physics theory and for our view of how the universe developed.

Is there more?

Neutrinos play a significant role in the energy production of the stars and the sun, and they are involved in the cataclysms of supernovae. They move near the speed of light, carry no charge, have very little mass by the standards of other elementary particles, and are governed by only two of the four fundamental forces in nature: the weak force, which is responsible for the spontaneous production of neutrinos whenever a radioactive atom undergoes beta decay, and gravity, which holds us on earth and keeps planets in orbit around the sun. To a neutrino, solid matter like our planet is virtually transparent. This neutral particle has about one chance in one billion of interacting with the material of the earth even if it passes directly through as it travels from the sun to the outer reaches of space.

From a cosmological standpoint, neutrinos and photons dominate the universe in sheer numbers, far outnumbering the few remaining protons and neutrons left over from the big bang. We know the vast number of neutrinos in the cosmos through our observation of other particles. Roughly, at any time, a billion neutrinos occupy one cubic meter of space with a billion photons and only one proton. The significance of this phenomenon involves the neutrino's mass. Photons are massless, but the combined effect of even a small mass of each of the billions of neutrinos per cubic meter together with the mass of the protons occupying the same space could seriously affect the universe through gravity.

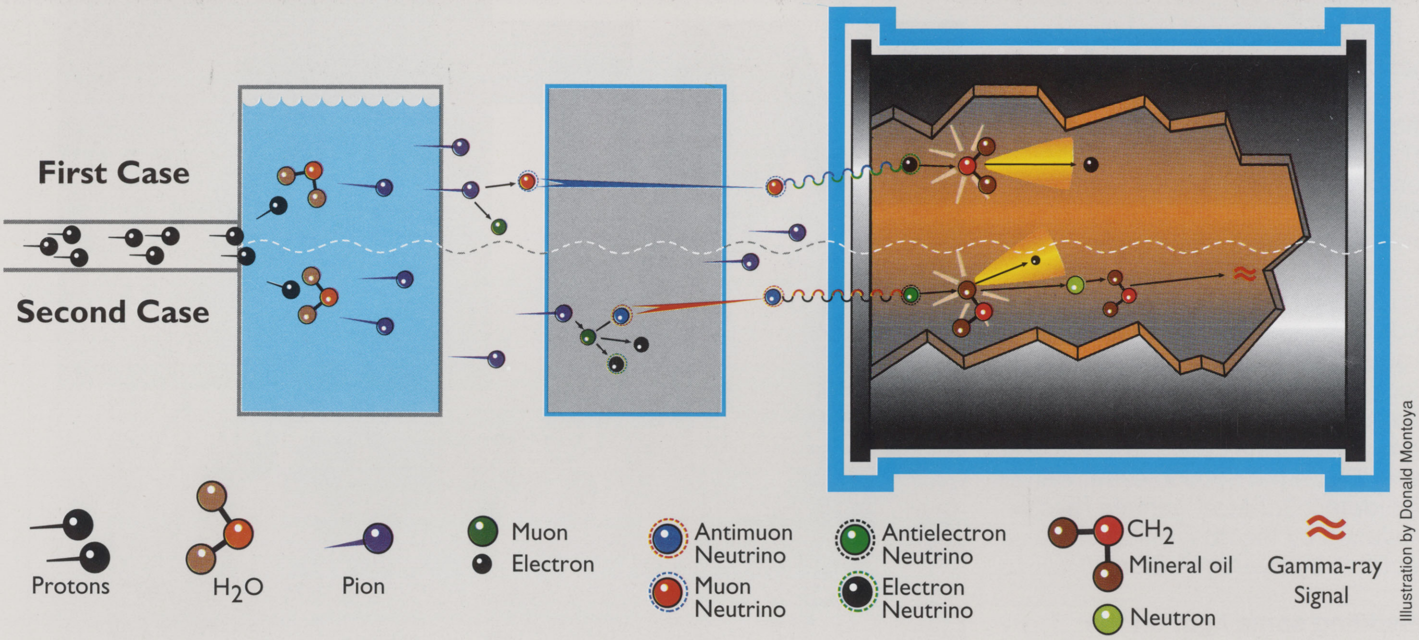
The attractive force of gravity depends on the mass of an object. The more massive an object is, the stronger the attractive force it exerts on other objects around it. A ball thrown in the air would continue on forever if the earth's mass were too small. The earth would not be able to exert enough gravitational "pull" to bring the ball back down. How the universe develops therefore depends on the total particle mass present. A small neutrino mass would have no influence on the expansion of the universe. The universe would probably expand outward forever; perhaps slowing gradually, but never stopping. But a massive neutrino could help slow the expansion as the particles exert a gravitational pull on one another and possibly cause the universe to eventually contract. A neutrino mass in the range accessible by the Los Alamos experiment could therefore have major long-term effects on the ultimate fate of the universe.

Mixing flavors

The question of the existence of neutrino oscillations has been a motivating force in a number of experimental efforts worldwide. Much of this motivation dates back to experiments involving solar neutrinos, which are part of the chain of reactions that fuel the sun and generate the energy that sustains life on earth. The reactions release electron neutrinos that are emitted in all directions from the center of the sun to the surface. Billions then travel 93 million miles to earth unimpeded by other particles along the way. In 1967, Raymond Davis and co-workers began a solar-neutrino experiment that has gone on for 20 years. Their detector, which uses chlorine as the medium, was placed deep in the Homestake Gold Mine in South Dakota to avoid background interference from incoming cosmic rays. A significant deficit was observed in the number of solar neutrinos predicted by detailed models of the sun's interior. This neutrino "shortfall" was recently confirmed by several other underground detectors that used different techniques and measured a solar neutrino flux of only two-thirds of what it should have been according to theory. This observed deficit, known as the "solar-neutrino problem," led scientists to postulate that either neutrinos change from one type to the other as they travel out from the center of the sun or that there has to be an unknown astrophysical explanation.

We can't go to the center of the sun to observe neutrino oscillations, but modern-day accelerators allow us to create neutrinos in the laboratory and mimic processes that occur in the sun. Although neutrinos can be copiously produced under laboratory conditions, the strength of neutrino interactions is so weak that measuring the few that do occur has challenged both technological and scientific "imagination" in detector designs and experimental setups. Additionally, neutrinos have brought about a new partnership between the ancient science of astronomy and a relative newcomer, particle physics.

With the aid of the proton accelerator at the Los Alamos Meson Physics Facility (LAMPF), we are observing neutrino events and separating these events by neutrino type. LAMPF produces a high intensity of neutrinos of suitable energy and type for these experiments. Protons from the accelerator interact with particles in a water target, producing pions among other particle debris. These pions travel downstream to a thick steel shield where they stop and eventually decay into muons and muon neutri-



Protons from the LAMPF accelerator interact with particles in a water target, producing pions, which travel downstream to a thick steel shield where they stop and eventually decay into muons and muon neutrinos. Over a trillion muon neutrinos per second travel through the steel shield unimpeded and on to the LSND. In the first case, a number of muon neutrinos may oscillate to electron neutrinos, which interact with the carbon atoms in the mineral oil to produce electrons that travel a short distance in the oil and excite the surrounding CH_2 molecules before coming to rest. The deposited energy in the CH_2 molecules is then transferred to the scintillator molecules, which amplify and release the energy in the form of isotropic light. The electrons also produce Cerenkov light, which is emitted in a cone that extends along the trajectory of the electron as it travels above the speed of light through the oil. In the second case, muons come to rest and decay into low-energy electrons, electron neutrinos, and antimuon neutrinos. If oscillation occurs, the antimuon neutrinos will transform into low-energy antielectron neutrinos, which interact with hydrogen atoms in the oil and produce neutrons and low-energy electrons. Gamma rays are also produced by the absorption of the neutrons with hydrogen atoms.

nos. Over a trillion muon neutrinos per second travel through the steel shield unimpeded and on to the LSND further downstream. Other particle debris, including neutrons, protons, and electrons, are stopped in the steel shield.

Cosmic rays in the upper atmosphere produce muons through particle decay. An extra layer of steel shielding above the LSND protects the detector from the incoming cosmic particles during experimental runs. In addition, a "veto" shield is wrapped around the LSND so that the most penetrating cosmic rays can be detected. However, these naturally produced cosmic muons are very useful in helping us calibrate the system to determine energy resolution and to monitor the performance of the experiment. Moreover, because the LSND is sensitive to supernovae events, the detector is constantly operational should one occur. In times of diminishing funds, our novel detector has allowed us to get as much leverage as possible in the continued investigation of physical phenomena.

The LSND contains 1,220 light-detecting phototubes, 180 tons of mineral oil consisting of molecules of one carbon atom per two hydrogen atoms (CH_2), and a small amount of scintillator powder that amplifies the light signals from which we reconstruct each neutrino event. We find a few events after searching through hundreds of millions of triggered events that catch the attention of the detecting system. Because the oscillation-event rate is expected to be so small (one event each week or less), a large number of protons are needed to produce the pions that eventually decay to the neutrinos that are eventually detected. The number of neutrinos produced is directly proportional to the number of protons that interact in the water target. Each proton from the LAMPF accelerator has a 10% probability of eventually producing a neutrino; therefore, the greater the number of protons, the greater our chances of detecting neutrino events and perhaps neutrino oscillations.

In our search for neutrino oscillations, we are investigating two cases of pion and muon decay. In the first case, muons and muon neutrinos are produced as pions decay "in flight" on their path toward the LSND. The momentum of an in-flight pion is transferred to the decay particles: muons and muon neutrinos. After this in-flight decay process, muon neutrinos may oscillate to electron neutrinos, which then interact with the carbon atoms in the mineral oil. Such an interaction would produce high-energy electrons primarily between 60 and 160 MeV. These electrons travel a short distance through the oil and excite the surrounding CH_2 molecules before coming to rest. Some of the deposited energy in the CH_2 molecules is then transferred to the scintillator molecules, which release the energy in the form of light (photons). This type of light is isotropic—that is, light in all directions.

In the second case, those pions that decay at rest produce muons. At rest, muons decay into low-energy electrons, electron neutrinos, and antimuon neutrinos. If oscillation occurs, the antimuon neutrinos will transform into low-energy antielectron neutrinos mostly between 36 and 52 MeV. These antielectron neutrinos interact with hydrogen atoms in the oil and produce neutrons and low-energy electrons. We can distinguish low-energy electrons from the high-energy electrons detected in the first case. But in the second case, we also detect 2.2-MeV gamma rays produced by the absorption of the neutrons by hydrogen atoms.

Shedding some light on the problem

The phototubes inside the LSND detect both isotropic light and Cerenkov radiation, which is another type of visible light generated by electrons as they pass through the oil. Like a shock wave, Cerenkov light is emitted at a fixed angle radiating in a cone that extends along the trajectory of an electron as it travels above the speed of light through the oil. The information gleaned from isotropic and Cerenkov light provides the position and energy of each electron. Isotropic light allows us to determine the energy and position of low-velocity particles, whereas Cerenkov light tells us the direction that the high-velocity electrons traveled. When a photon hits a phototube, it creates an electronic pulse, which is amplified and transferred through cables to fast electronics where the pulse is converted to two numbers: the pulse height, or charge, and the absolute time when each phototube is hit. With these two pieces of information, a multiprocessor system combines the data and then builds each neutrino event. The events are reconstructed on-line and stored on tapes for later analysis and interpretation.

We sort neutrino events by energy to obtain a distribution that serves as a good indicator of oscillations. This plot helps us interpret signals from the detector by showing the variation in the neutrino event rate as a function of energy. Background from all other neutrino processes, like cosmic-ray interference, is subtracted out. In the first case, we look at the spatial and energy distribution of high-energy electrons between 60 and 160 MeV for electron neutrinos, and in the second case, we look at the spatial and energy distribution of moderate-energy electrons between 36 and 52 MeV in coincidence with 2.2-MeV gamma rays for antielectron neutrinos. These two energy "bins" are the prime regions where oscillations from muon neutrinos to electron neutrinos in the first case and from antimuon neutrinos to antielectron neutrinos in the second case are most likely to occur.

The experiment is operating, the data being collected are of good quality, and the accelerator is running smoothly. We are seeing neutrino candidates with the kind of signal that we expect. However, much detailed study remains to be done. Research does not come with guarantees, and so we can only look at how nature really works. We are on guard against the temptation of making the data into our own image of it. Time alone will tell.

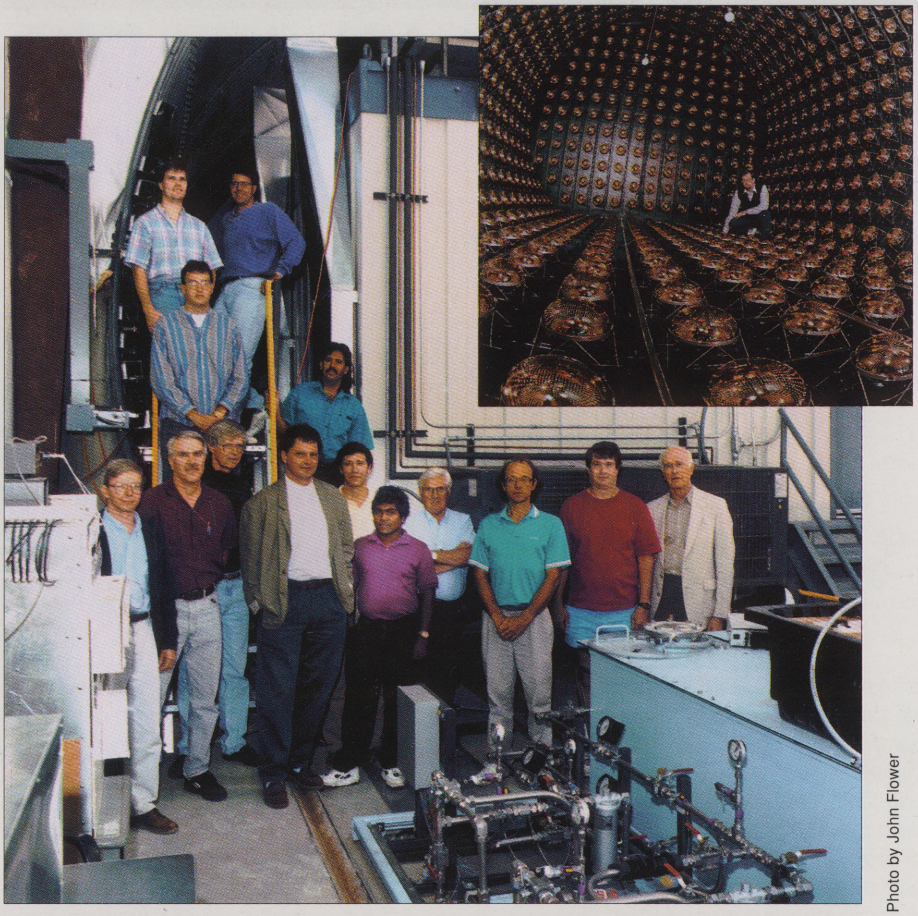


Photo by John Flower

Members of the LSND experiment are shown near the entrance to the neutrino tunnel where the detector is located. The blue tank on the right is an overflow reservoir, which contains excess mineral oil from the main detector tank. The data-acquisition electronics are located in the electronics hut, which is the beige building in the background. The inset shows a portion of the phototubes that cover the inside of the LSND tank.

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